International Journal of Advanced Information Science and Technology (IJAIST) *ISSN: 2319:2682*
Vol.4, No.12, December 2015 DOI:10.15693/ijaist/2015.v4i12.108-114

Wheel Alignment Analysis on the Racing Kart Steering Linkage

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***Abstract*—Since there are no suspension system and differential gearing on racing karts, a special wheel alignment is installed so that inner rear wheel is lifted when turning. Depending on the adjustment of wheel alignment on the racing karts, it becomes an important indicator of control stability and control performance. However, the driver can adjust the kart freely accordingly to the characteristic of the circuit and road condition. On this paper, steering linkage of racing kart was modeled on 3-dimensional space. Analytical model was developed and simulation was performed based on the basic algorithm derived from the modeling. Also, the characteristic was analyzed based on wheel alignment and its effect on driving performance of the kart was presented and demonstrated.**

Index terms –Racing Kart, Steering linkage, Wheel alignment.

I. INTRODUCTION

Since Jeonnam Youngam F1 Korean series game in 2010, the fourth game was held this year and it played a stepping up role in raising interest and standard of national motor sports. Therefore, a demand of systematic driving training has been increasing thanks to sudden interest in training racing driver in the country. Racing kart has a simple structure consisted of 80cc one-cylinder 2 cycle engine, frame, seat, steering mechanism, and brakes. It is used as a training course by professional driver students due to its similarity in driving mechanism of formula racing cars when learning its driving characteristic. Racing kart has low ground clearance and driving impact is delivered to the driver at the high speed of 100km/h. It has high acceleration performance due to its power ratio per weight. Also, 2 cycle engine has a small steering gear ratio of 1:1.5, which accounts for accelerating pedal control capacity and wheel rotation of steering handle within wide range of rotation rate (12,000rpm). It is useful for drivers in learning turning skills. In order for the kart to turn without gliding movement, the traces of all wheels should draw a concentric circle to be idealistic. When steering, extension line of central line in front wheel spindle should intersect at 1 point with extension line of rear axle at the same time.

Racing kart does not have suspension system and differential gearing, unlike regular cars. It steers with Ackerman steering linkage, which requires a special wheel alignment. In figure 1, if the driver puts pressure to steer with the purpose changing the direction of the kart, then left and right front wheels rotate at a fixed steering angle. However, racing kart has spindle with large kingpin angle of inclination and caster installed. When it turns, the frame inside of front wheel rises above the ground and the frame outside of front wheel declines towards the road. At the same time, centrifugal force is applied on racing kart creating flexure and torsion on the frame, while weight inside decreases as its weight moves outside.

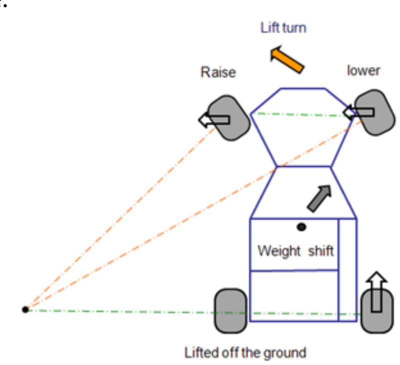

Figure 1. Racing kart behavior at cornering

Such weight movement causes inside rear wheels to get lifted off the ground allowing the kart to smoothly turn on three-wheel.Therefore, racing kart has a consistent relationship with wheel alignment that optimizes its straightness, stability, steering performance, and dynamic stability of returning to straight position from steering position. Characteristics of wheel alignment of racing kart include controlling camber and caster by widening or shortening front wheel tracking using spacer on wheel arm, extending or shortening the length of tie rod according to linking point on spindle arm, or changing the kingpin angle by turning kingpin adjuster. However, the driver adjusts wheel alignment based on characteristics of the circuit's straight and curved section, climate of the circuit, weather, and road condition, as well as personal experience and experimental test. Because of this, professional driver students have difficulty in understanding changes in wheel alignment followed by steering linkage and proper wheel alignment for driving performance.

On this paper, Ackerman steering linkage on kart will be basically modeled and interpreted in 3-dimensional space, and performance of the steering linkage through simulation will be shown. Also, change in characteristics of wheel alignment based on Ackerman geometry and steering linkage structure change in relation with steering linkage performance was analyzed.

II. Kart SteeringLinkage Mechanism

Figure 2 (a), (b), and (c) shows racing kart's steering linkage modeled geometrically for analysis and its structure consists of steering shaft, 2 tie-rods that are centralized towards steering axis, spindle, spindle arm, and wheel arm. Kart's steering linkage forms a trapezoid along with wheel arm, tie-rod, and spindle when it moves straight and it is called trapezoid steering linkage or Ackerman steering linkage. A gap is formed between left and right front wheel steering angle when turning with trapezoid steering linkage. On Figure 2 (a) and (b), axis of coordinates shows kart's rear direction on +X axis, right side on +Y axis, and top direction on +Z axis.Steering axis is a rotation joint, and left and right tie-rod is connected with ball joint with spindle on steering axis. Spindle works as rotation joint on the frame due to kingpin, and wheel arm is connected to spindle and works as rotation joint with a tire installed. When the driver turns steering handle with the purpose to steer, steering axis rotates and such rotation is delivered as a displacement to spindle arm connecting point due to tie-rod. Then, the wheel is steered as spindle rotates on kingpin axis on Figure 2 (c).

Figure 2 (a), (b), and (c) show that on kart's front wheels' camber, caster, kingpin's angle of inclination, and tow are designed in a way that the driver can conveniently control each component's angle.

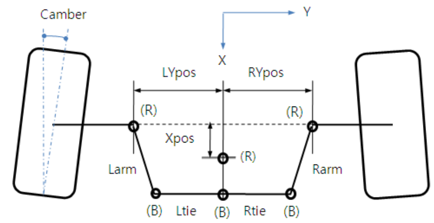

Figure 2(a). Steering linkage top view

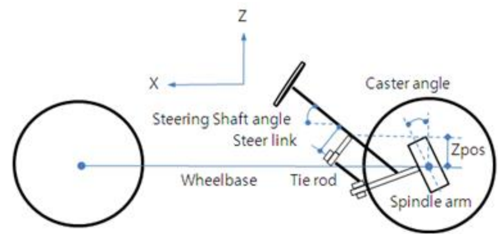

Figure 2(b). Steering linkage side view

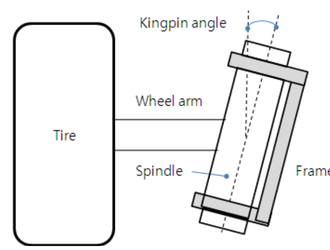

Figure 2(c). Steering linkage front view

III. Steering Linkage Analysis

A. Wheel arm coordinatesequation

If Let Figure 3 be wheel arm's location coordinate axis. XYZ coordinate system has spindle's base side as the absolute coordinate axis. xyz coordinate system has wheel arm and spindle's connecting point B as coordinate system.

Location vector $R_c$of Point C on XYZ axis is displayed as addition of location vector R_B of Point B on XYZ axis and location vector $R_{c/2}$ of relative Point C on xyz axis.

$$R_C = R_B + R_{C/2} \quad (1.1)$$

$$R_c = \begin{bmatrix} 0 \\ 0 \\ L_1 \end{bmatrix} + \begin{bmatrix} 0 \\ -L_2 \cos\alpha \\ L_2 \sin\alpha \end{bmatrix} \quad (1.2)$$

When the driver enters steering input, spindle and wheel arm rotate steering angle of θ on the center of Z axis,kingpin angle of α on the center of X axis, and caster angle ofγ on the center of Y axis. When it rotates at the center of each Z axis, X axis, and Y axis, then rotation matrix can be defined as below when R_z, R_X, and R_Y are found.

$$R_Z = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2.1)$$

$$R_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{bmatrix} \quad (2.2)$$

$$R_Z = \begin{bmatrix} cos\gamma & 0 & sin\gamma \\ 0 & 1 & 0 \\ -sin\gamma & 0 & cos\gamma \end{bmatrix} \quad (2.3)$$

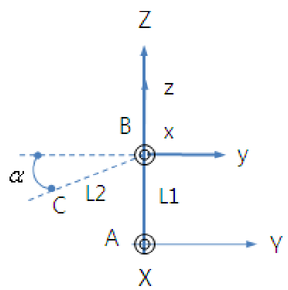

Figure 3(a). Coordinate system before rotation

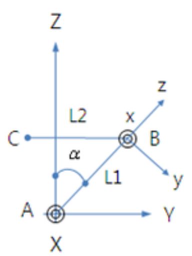

Figure 3(b). Coordinates system after kingpin rotation

Converted matrix can be obtained by using R_z, R_X, and R_Y and multiplying on both sides.

$$R_{CZXY} = R_Y R_X \begin{bmatrix} 0 \\ 0 \\ L_1 \end{bmatrix} + R_Y R_X R_Z \begin{bmatrix} 0 \\ -L_2 cos\alpha \\ L_2 cos\alpha \end{bmatrix} \quad (3)$$

If $L_1 = 0$, the absolute coordinate axis moves to wheel arm and spindle's connecting point B and simplified equation of left wheel arm location vector can be obtained.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_Y R_X R_Z \begin{bmatrix} 0 \\ -L_2 cos\alpha \\ L_2 cos\alpha \end{bmatrix} \quad (4)$$

Such matrix can be found below when rotation matrix R_z, R_X, and R_Y are synthesized here.

$$R_Y R_X R_Z = \begin{bmatrix} \cos\theta\, cos\gamma + \sin\theta \sin\alpha\, sin\beta & -\sin\theta\, cos\gamma + \cos\theta \sin\alpha\, sin\,\beta & \cos\alpha\, sin\gamma \\ \sin\theta\, cos\,\alpha & \cos\theta\, cos\,\alpha & -sin\alpha \\ \cos\theta \sin\alpha + \sin\theta \sin\alpha\, cos\,\gamma & \sin\theta \sin\alpha + \cos\theta \sin\alpha\, cos\gamma & \cos\alpha\, cos\gamma \end{bmatrix} \quad (5)$$

Using the same method as above, right wheel arm's location vector equation result is the same as left wheel arm location vector equation but with signs changed.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_Y R_X R_Z \begin{bmatrix} 0 \\ L_2 cos\alpha \\ -L_2 cos\alpha \end{bmatrix} \quad (6)$$

B. Spindle arm coordinates equation

Let's set up spindle arm's location coordinate axis. XYZ coordinate system is the absolute coordinate system having connecting point of spindle arm and spindle as its base. In Figure 4, there are 2 connecting points that control tie-rod length on left spindle arm and they are defined as such on below.

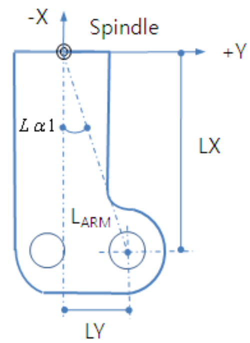

Figure 4. Left spindle arm top view

$$LX = L_{ARM} \cos(L_{\alpha 1})$$
$$LY = L_{ARM}\, sin(L_{\alpha 1})$$
$$LZ = 0 \quad (7)$$

The direction of rotation of spindle arm is the opposite direction of kingpin angle. Early equation of spindle arm location vector is obtained when rotation matrix with (-) direction on X axis is multiplied. It is defined below as such.

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & sin\alpha \\ 0 & -sin\alpha & cos\alpha \end{bmatrix} \begin{bmatrix} L_{ARM}\, cos(L_{\alpha 1}) \\ L_{ARM}\, sin(L_{\alpha 1}) \\ 0 \end{bmatrix} \quad (8.1)$$

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \begin{bmatrix} L_{ARM}\, cos(L_{\alpha 1}) \\ L_{ARM}\, sin(L_{\alpha 1})\, cos\alpha \\ -L_{ARM} \sin(L_{\alpha 1})\, sin\alpha \end{bmatrix} \quad (8.2)$$

Here we know LX and LY, L_{ARM} and $L_{\alpha 1}$ are found using the equation below.

$$L_{ARM} = \sqrt{LX^2 + LY^2} \quad (9.1)$$
$$L_{\alpha 1} = tan^{-1} \quad (9.2)$$

Using the same way as wheel arm, spindle arm's coordinate equation is obtained by using early spindle arm location vector.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_Y R_X R_Z \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \quad (10)$$

C. Steering link coordinates equation

Let's set up location coordinate axis of steering link on Figure 5. XYZ coordinate system is the absolute coordinate system based on the base side of steering axis and xyz coordinate system is the coordinate system based on connecting point E of steering link and coordinating axis. Location vector R_F of Point F on XYZ axis is shown as addition of location vector R_Z of Point E on XYZ axis and location vector $R_{Z/2}$ of relative Point F on xyz axis.

$$R_F = R_Z + R_{F/2} \quad (11.1)$$

$$R_F = \begin{bmatrix} 0 \\ 0 \\ L_4 \end{bmatrix} + \begin{bmatrix} L3 \\ 0 \\ 0 \end{bmatrix} \quad (11.2)$$

Steering axis and steering arm rotate steering angle of θ_1 on the center of Z axis. Spindle and wheel arm rotate caster angle of γ_1 on the center of Y axis.

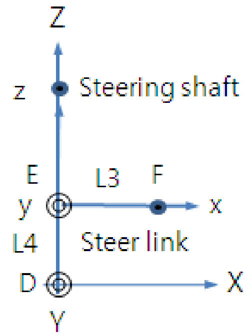

Figure 5(a). Steering link side view

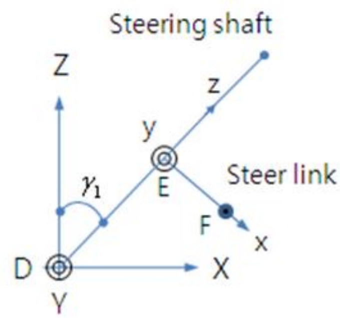

Figure 5(b). Steering link after rotation

When rotating at the center of Z axis and Y axis, rotation matrix is R_Z and R_Y, and rotation is defined as such on below when it is synthesized.

$$R_Z = \begin{bmatrix} cos\theta_1 & -sin\theta_1 & 0 \\ sin\theta_1 & cos\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (12.1)$$

$$R_Z = \begin{bmatrix} cos\gamma_1 & 0 & sin\gamma_1 \\ 0 & 1 & 0 \\ -sin\gamma_1 & 0 & cos\gamma_1 \end{bmatrix} \quad (12.2)$$

$$R_Z = \begin{bmatrix} cos\gamma_1 cos\theta_1 & -cos\gamma_1 sin\theta_1 & sin\gamma_1 \\ sin\theta_1 & cos\theta_1 & 0 \\ -sin\gamma_1 cos\theta_1 & sin\gamma_1 sin\theta_1 & cos\gamma_1 \end{bmatrix} \quad (12.3)$$

Using $R_Y R_Z$, converted matrix can be obtained when it is multiplied on both sides. Let L4 = 0 and the absolute coordinate axis moves to connecting point E, then simplified location vector equation of steering link can be obtained.

$$R_{FZY} = R_Y R_Z \begin{bmatrix} L3 \\ 0 \\ 0 \end{bmatrix} \quad (13.1)$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_Y R_Z \begin{bmatrix} L3 \\ 0 \\ 0 \end{bmatrix} \quad (13.2)$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} cos\gamma_1 cos\theta_1 & -cos\gamma_1 sin\theta_1 & sin\gamma_1 \\ sin\theta_1 & cos\theta_1 & 0 \\ -sin\gamma_1 cos\theta_1 & sin\gamma_1 sin\theta_1 & cos\gamma_1 \end{bmatrix} \begin{bmatrix} L3 \\ 0 \\ 0 \end{bmatrix} \quad (13.4)$$

When rotation matrix is multiplied and organized, vector of given θ_1, γ_1 steering link is found as below.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_Y R_Z \begin{bmatrix} L3\ cos\gamma_1 cos\theta_1 \\ L3\ sin\theta_1 \\ L3\ sin\gamma_1 \end{bmatrix} \quad (14)$$

D. *Steering axis position*

On Figure 6, $(X_{LSA}, Y_{LSA}, Z_{LSA})$ is relative positon coordinate for left spindle arm of $X_L Y_L Z_L$. $(X_{RSA}, Y_{RSA}, Z_{RSA})$ is relative position coordinate for right spindle arm of $X_R Y_R Z_R$. (X_S, Y_S, Z_S) is defined as relative coordinate for steering link of $\overline{XYZ}$. Position vector equation for new coordinate can be found below. $LY_{POS}, LX_{POS}, X_{POS}, Y_{POS}$ are given as design variables of kart.

$$\begin{bmatrix} \bar{X}_{LSA} \\ \bar{Y}_{LSA} \\ \bar{Z}_{LSA} \end{bmatrix} = \begin{bmatrix} X_{POS} - X_{POS} \\ Y_{POS} - LY_{POS} \\ Z_{POS} - Z_{POS} \end{bmatrix} \quad (15.1)$$

$$\begin{bmatrix} \bar{X}_{RSA} \\ \bar{Y}_{RSA} \\ \bar{Z}_{RSA} \end{bmatrix} = \begin{bmatrix} X_{RSA} - X_{POS} \\ Y_{RSA} + RY_{POS} \\ Z_{RSA} - Z_{POS} \end{bmatrix} \quad (15.2)$$

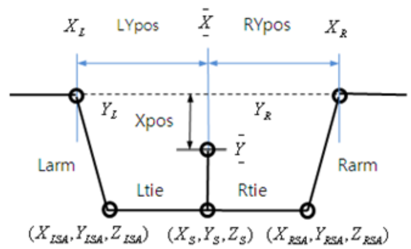

Figure 6. Location of axes

Distance between left spindle arm axis coordinate and steering axis coordinate is same as the length of left tie-rod. Also, distance between right spindle arm axis coordinate and steering axis coordinate is same as the length of right tie-rod, and it can be found by using the following equation.

$$\mathrm{LDIS} = \sqrt{(\bar{X}_{LSA} - X_S)^2 + (\bar{Y}_{LSA} - Y_S)^2 + (\bar{Z}_{LSA} - Z_S)^2} \quad (16.1)$$

$$\mathrm{RDIS} = \sqrt{(\bar{X}_{RSA} - X_S)^2 + (\bar{Y}_{RSA} - Y_S)^2 + (\bar{Z}_{RSA} - Z_S)^2} \quad (16.2)$$

V. SIMULATION AND RESEARCH RESULTS

A. *Simulation Model and Parameters*

Racing kart's position, length, angle, and various parts of steering linkage were measured on Table 1. Racing kart's wheel arm coordinate equation, spindle arm coordinate equation, steering link coordinate equation,and steering axis position of steering linkage were expressed on 3-dimensional space by using four algorithms. Racing kart's steering linkage analysis module was developed using engineering software called "Matlab." Two tie-rod lengths and steering axis height were used as design variables for steering linkage. A simulation was performed based on changes in aspects of 4-

wheel alignment in terms of kingpin angle of inclination, caster, tire offset, and steering geometry when steering rotation angle is increased from0°to 30°

Our simulation settings and parameters are summarized in table 1.

Data	Dimension
Zpos	1.59cm
Xpos	5.24cm
LYpos	26.98cm
RYpos	30.6cm
Caster	15°
Kingpin	15°
Wheelbase	102.8cm
Tire offset	11.4cm
Steer link	6.35cm
Steer shaft angle	44.58°
LX	10.79cm
LY	1.35cm
RX	10.79cm
RY	-1.35cm
Left tie-rod length	25.65cm/29.29cm
Right tie-rod length	25.65cm/29.29cm
Steer shaft height	49cm/55cm

B.research results

Kingpin angle is formed by kingpin's central line and straight line on the surface side. It lifts the front part of kart when steering handle is steered in random direction and it gives dynamic stability due to the weight of kart when it moves straight. Smaller the kingpin offset,more steering force is required. In Figure 7, kingpin is fixed at certain values (10° or 15°). Caster value is increased from 10° to 15°, which causes outer wheel to increase (+) camber to (-) camber but inner wheel increases to (+) camber. If kingpin angle is increased from 10° to15°, outer wheel camber is decreased while inner wheel camber is increased.

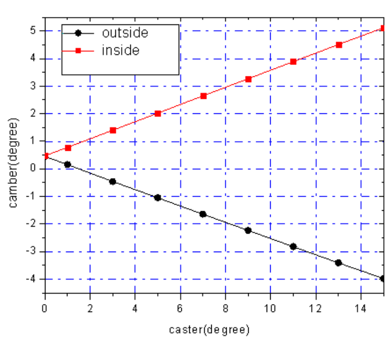

Figure 7(a). caster vs camber(kingpin 10 deg.)

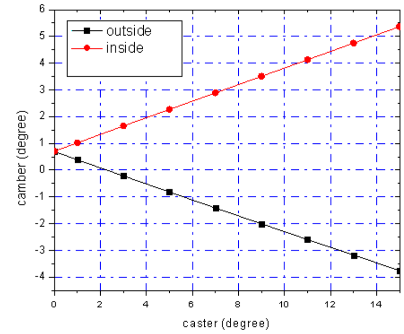

Figure 7(b). caster vs camber(kingpin 15 deg.)

On Figure 8, when camber angle is fixed at certain values (5° or 15°) and kingpin value is increased from 0° to 15°, outer wheel camber increases but inner wheel camber decreases. It could be seen that the effect of (+) camber increases as kingpin angle increases. On the other hand, if kingpin is increased excessively, it can decrease cornering performance as moving straight stability increases. Depending on how much caster increases, each front wheel's (-) camber and (+) camber increase.

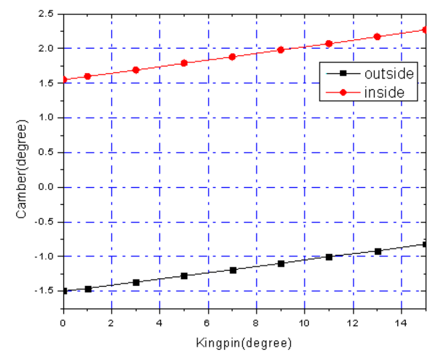

Figure 8(a). kingpin vs caster(camber 5 deg.)

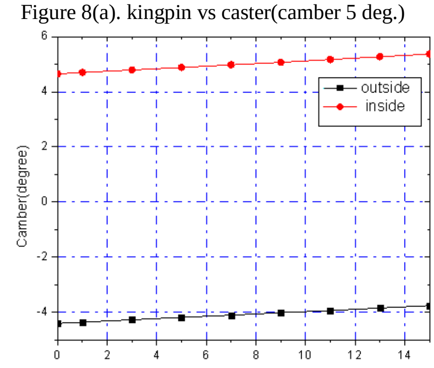

Figure 8(b). kingpin vs caster(10 deg.)

Ideally, wheels need to be in contact with the road in order to always get the highest pulling capacity from the road. However, no suspension system is installed on kart, which causes a problem with kart coming in a contact on the road surface when camber angle's change is increased and certain (+) camber is reached. In contrast, caster decrease the effect of kingpin's angle.High speed steering feel is closely related to driving stability on racing kart. Steering feel performance accurately takes driver's steering intention into account so thatkart's responsiveness and steering control coincide, and the driver needs to small modification to steering angle. In contrast, steering feel is poor when it responds too sensitively to small steering angle or too dully that it creates substantial phase difference. Such steering feel is subjective assessment and it is difficult to quantify human's senses. Overall, this paper suggests a method to control by compromising caster angle to have 1/2 of kingpin angle.Racing kart's wheel track of front wheel increases when tire offset increases so its weight transfer decreases when cornering from inside towards outside and steering force increases as kingpin offset becomes bigger.

On Figure 9, kingpin angle is fixed 10° and tire offset is increased from 3 inch to 4.5 inch,which will show tire displacement depending on various caster angles. Tire displacement becomes lower as the kart frame turns (-) direction depending on increase in tire offset. Also, tire displacement becomes lower significantly as the kart frame turns (-) direction depending on caster angle increases from 3° to 15°.

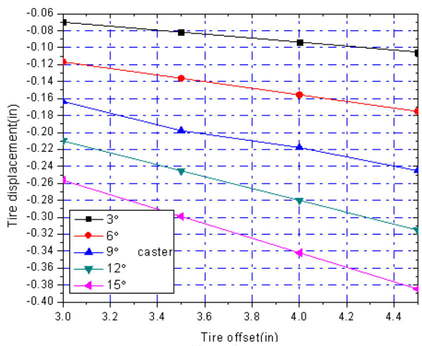

Figure 9.tire displacement vs tire offset for kingpin 10 deg.(inside wheel, input angle 30 deg.)

There are two kinds of tie-rod length adjustment and two connecting points on external and interior of spindle arm. On the figure 10, when steering angle changes from 0° to 35°, difference between actual steering angle and theoretical Ackerman angle at small steering angle is small. On the other hand, there is a small difference between external wheel's steering angle and Ackerman steering angle on short tie-rod length, which serves as connecting point in internal side. When internal tie-rod is connected and the kart turns, over-steering phenomenon and turning speed decrease. At the same time, turning speed increases when the kart turns and understeering phenomenon decreases after external tie-rod is installed.

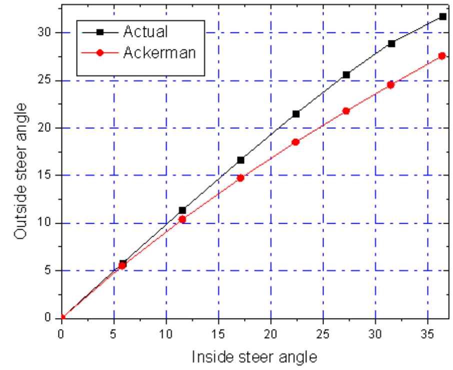

Figure 8(a). outside vs inside steer angle(kingpin 12 deg., caster 6 deg., inside spindle arm)

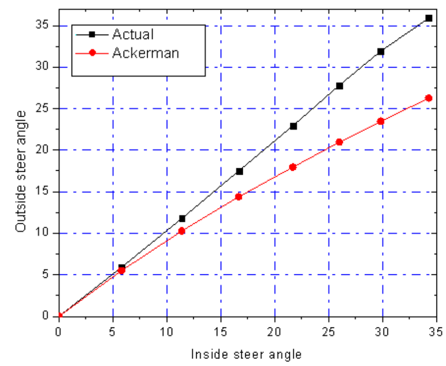

Figure 9(b). outside vs inside steer angle(kingpin 12 deg., caster 6 deg., outside spindle arm)

VI. Conclusion

In this research, racing kart's steering linkage was defined on 3-dimensional space. Steering linkage's location vector equation was found by inducing wheel arm, spindle arm, and steering linkage, while rotation matrix was synthesized on the early position vector, which has an absolute coordinate as the base. A simulation was carried out by using induced basic algorithm to develop an analysis module. Through analysis of racing kart's steering geometry, characteristics due to changes in wheel alignment for special demand were analyzed, and how these characteristics can affect kart's driving performance was shown and proven. Driving stability and performance, followed by changes in wheel alignment, are important indicators of driving performance.

Acknowledgement

This work was supported by research fund of Ajou Motor College and Chungnam National University

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